# OZONE EFFECTS ON CROPS IN ONTARIO AND RELATED MONETARY VALUES

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Ministry of the Environment
Ontario

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# *OZONE EFFECTS ON CROPS IN ONTARIO AND RELATED MONETARY VALUES*

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*ONTARIO MINISTRY OF THE ENVIRONMENT*

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# *OZONE EFFECTS ON CROPS IN ONTARIO AND RELATED MONETARY VALUES*

*BY*

**S. N. Linzon, R. G. Pearson, J. A. Donnan, and F. N. Durham**

## 1. *INTRODUCTION*

*This chapter on crop damage forms part of a larger report on Oxidant Control Strategy for Ontario. Other chapters will deal with atmospheric influences and control technology. This chapter will document the degree and extent of oxidant crop damage in Ontario and the monetary benefits which would ensue if oxidants were reduced to levels which would cause no harm to agricultural crops.*

*Photochemical oxidant air pollution was first recognized in 1944 when Middleton et al (1950) observed toxic effects on vegetation in Los Angeles. The actual phytotoxic components were not positively identified until several years later. In 1958, Richards et al, ascribed grape "stipple" near San Bernardino, California to atmospheric ozone ($O_3$). Tobacco "weather fleck" observed at Beltsville, Maryland in 1952, and in southern Ontario in 1955 was ascribed to ozone in 1959 (Heggestad and Middleton 1959; Macdowall et al 1963). Etiological studies to determine the relationship between atmospheric ozone and unexplained needle injuries on eastern white pine trees were started in Canada in 1959 (Linzon, 1966) and in the United States in 1961 (Berry and Ripperton 1963).*

*In 1960, peroxyacetyl nitrate (PAN) was identified as the cause of specific symptoms on Romaine lettuce and Swiss chard (Stephens et al 1961). Studies on the effects of nitrogen dioxide ($NO_2$) on vegetation were reported in California in 1955 on weeds (Bendedict and Breen 1955) and in 1957 on pinto bean (Middleton et al 1958).*

*The main photochemical oxidants ($O_3$ PAN and $NO_2$) responsible for vegetation effects, are produced in the atmosphere under solar radiation from reactions between reactive hydrocarbons and nitrogen oxides emitted during the combustion of fossil fuels.*

*The characteristic symptoms of PAN injury on vegetation are glazing, silvering or bronzing of the undersurface of affected leaves of plants such as spinach, garden beets, lettuce and chard. Banding, or successive injuries on grasses, tomato and tobacco were found to be due to successive exposures to PAN in sensitive regions of expanding leaf tissue. Sensitive plants have been injured by 15 ppb of PAN in a 4 hr exposure. Light is necessary before, during, and after a fumigation by PAN to cause visible injury. Unlike ozone which builds up to a peak concentration before noon and usually degrades in late afternoon, PAN builds up to a maximum in the afternoon and persists for a longer period of time before degrading. PAN has not been extensively monitored in ambient air. A maximum concentration of 210 ppb was recorded in 1965 in downtown Los Angeles (Taylor 1969), 58 ppb in 1967 at Riverside (ibid), and 54 ppb in 1966 at Salt Lake City (Tingey and Hill 1967). PAN-like symptoms have been observed on tomato plants in southern Ontario, but PAN levels have rarely exceeded 5 ppb in these areas. Thus it is not expected that PAN poses any significance for crop damage in Ontario.*

*In Ontario, the maximum 1 hr, 24 hr and annual concentrations of $NO_2$ measured in 1978 were 0.24, 0.12 and 0.046 ppm respectively. Sensitive plant species may be injured by a 2 hr exposure to about 6.0 ppm $NO_2$ under high light and to 2.5 to 3.0 ppm under low light (Taylor and Maclean 1970). These levels are considerably higher than $NO_2$ atmospheric levels measured in Ontario. The acute injury symptoms (lesions) on plant foliage caused by $NO_2$ are similar to those caused by sulphur dioxide ($SO_2$). Nitrogen dioxide can injure the same plant species as $O_3$, and in the same tissue and stage of development, but the injury symptoms are different, and approximately ten times as much $NO_2$ is required. Long-term exposures of plants to low concentrations of $NO_2$ (less than 0.5 ppm) may inhibit plant growth and increase the chlorophyll content. The effects of $NO_2$ on plant life have been determined mainly through experimental exposures.*

*Photochemical oxidants are known also to cause damage to some materials, contribute to atmospheric haziness, and impair respiratory function in humans. Materials are affected by ambient air $O_3$ concentrations ranging between 0.01 to 0.20 ppm (Sanderson, 1975). The most important materials affected are certain textiles, dyes, rubbers and plastics. The cracking of stressed rubber is well known, and it is necessary to add anti-ozonants in the manufacture of rubber products, such as tires. Visibility reduction due to oxidant smog was at first confined to the Los Angeles area in the late 1940's and early 1950's. Other areas of the world began to experience oxidant smog in the 1950's wherever there were sufficient sources of hydrocarbons and oxides of nitrogen, and whenever the meteorological circumstances were suitable (strong sunshine, light winds, and a capping subsidence inversion) (Munn, 1975). Haziness has been found to be increasing, with Lovelock (1972) showing this to be occurring in the*

*rural parts of the U. K., while Miller et al (1972) documented increases in haziness at airports near three cities in the U.S. At all three airports, during the period 1962-1971, there were three-to five-fold increases in the frequencies of reduced visibilities. Munn (1975) stated that in Canada winter frequencies of haziness have been decreasing in recent years in populated parts due to air pollution abatement programs, but in summer, haze frequencies are not decreasing, and in fact, have doubled in Eastern Canada during the period 1953 to 1971. Visibility reductions are also frequently caused by sulphate particulates which are outside the scope of consideration in this report.*

*There is a lack of good epidemiological studies on the effects of oxidants on human health. In controlled exposure studies* $O_3$ *has been shown to produce measurable changes in pulmonary functions (Bates 1975). These effects are enhanced in the presence of chronic lung disease. Also, in some areas, it is probable that* $O_3$ *has occurred at levels sufficient to produce the symptoms of dry cough, chest pain, and shortness of breath as found in controlled studies. Hazucha et al (1973) exposed eight normal subjects to 0.37 ppm* $O_3$ *together with 0.37 ppm* $SO_2$ *for a period of 2 hr, and found that the combination of gases produced an increasing loss in midexpiratory flow rates with time, as opposed to little or no loss in the presence of either of the individual gases. At a recent Symposium on the Biomedical Effects of Ozone held in North Carolina in March, 1982, a number of medical researchers presented results of controlled exposure studies. McDonnell (1982) found a significant increase in cough at 0.12 ppm* $O_3$*, and small and large changes in lung function at 0.12 and 0.024 ppm respectively. In a "real-life" study, children were found by Lippmann (1982) to be more sensitive to ozone, with significant lung function impairment occurring at 0.10 ppm* $O_3$*.*

*The significance of the effects of oxidants on materials, visibility and human health with regard to monetary values is not well documented. For this reason, this chapter will deal principally with ozone injury to agricultural crops and the associated economic impact.*

## *2. OZONE EFFECTS ON CROP PRODUCTIVITY*

*Foliar responses of crops to natural or artificial exposure with ozone have been well documented and used in the development of species and varietal sensitivity listings and in the preparation of predictive dose-response curves (Larsen and Heck 1976; Linzon et al 1975). However, these data may not be entirely effective in determining crop productivity (e.g., growth, yield, quality). Current information indicates that the severity of foliar injuries is not a reliable index of crop productivity (Reinert 1980) with some plant species displaying yield losses in the absence of visible injuries and vice-versa. Also, compensatory responses to ozone can produce rapid recovery from injury (Jacobson, 1980). Studies with soybeans (Tingey et al 1973), tomatoes (Oshima et al 1975) and alfalfa (Tingey and Reinert 1975) all support this concept. The exceptions to this general finding are cases where the harvested product is the foliage and where foliar injury development coincides with the rapid growth or development of the harvested product (Linzon et al 1975).*

*Although the adverse effects of ozone exposure on crop yield have not been as extensively documented as has been the case with foliar injury, there are nevertheless, a number of reports on this topic. Any assessment of yield or quality parameters under field conditions is complicated by the ubiquity of ozone exposure, the effect of meteorological variables on ozone distribution within crop canopies, and the difficulty in establishing ozone-*

*free control plots. Numerous biotic (pathogen/genetics) and abiotic factors (temperature, humidity, light, and soil moisture) within the environment must also be taken into account. These difficulties have been partially overcome by recent progress which has been made in the development of field assessment techniques for plant growth and yield (Reinert 1980). These include open-top field chambers, pollutant exclusion methods, open-air fumigations, ambient air pollutant gradients and chemical protectants. The most recent program which has been developed to utilize the most generally accepted open-top field chamber technique is the National Crop Loss Assessment Network (NCLAN). It is comprised of a group of government and non-government organizations in the U.S. who are attempting to determine the immediate and long-term effects of* $O_3$, $SO_2$, $NO_2$, *and their mixtures on agricultural crop production through field studies, crop production modeling and economic analysis. The basic experimental design consists of the exposure of agronomically important crop species in open-top field chambers which have been adapted to permit the addition or deletion of pollutant gases allowing specific pollutant regimes to be imposed on the test species. The research is being conducted at five regional field sites across the U.S. (NE, SE, Central, NW and SW) selected to represent distinctly different geographical and climatological conditions and crop species. The dose-response information generated from these studies will at first be empirical multivariate plant yield response functions and these will be followed by more complex functions that take into consideration the effects of edaphic, climatic, and genetic factors on crop yield response to air pollutants.*

*In the first two years of the NCLAN study (1980, 1981) the field exposures have concentrated on ozone which has been metered into or excluded from the*

*exposure chambers during the growing season of the various crops on a 7 hr per day basis (0900-1600 S.T.) when ambient ozone levels are normally elevated. This dose concept with ozone being added to existing ambient concentrations that gradually increase throughout the day was first utilized by Heagle et al (1979a) and has additional significance in regard to its use in support of the revised U.S. primary and secondary national ambient air quality standards (NAAQS) for photochemical oxidants (Lokey et al 1979). According to Heagle et al (1979a) the 7-hr-mean best represents the dose for all stages of plant growth for the period of each day when the plants are most sensitive to ozone, thereby describing the ozone dose in a biologically relevant way. The first report from the 1980 NCLAN project (Heck et al 1982) included earlier dose-yield response data from Heagle and Heck (1980) and demonstrated yield reductions in the various crops as follows: soybean: 10%, peanut: 14-17%, turnip: 7%, head lettuce: 53-56% and red kidney bean: 2%. These yield reductions were associated with non-filtered chamber seasonal 7 hr/day mean $O_3$ concentrations of 0.042, 0.056, 0.034, 0.106, and 0.053 ppm, respectively, when compared to a carbon filtered background control value of $O_3$ of 0.025 ppm. The yield data were subsequently utilized in several predictive regression models to develop yield loss functions at 0.06 and 0.10 ppm 7 hr seasonal mean concentrations. The 0.06 ppm seasonal mean was selected on the basis of U.S. $O_3$ data which was analyzed by Lokey et al (1979) and is the maximum mean concentration expected in many parts of the U.S. when the current 1 hr standard of 0.12 ppm is just met. On the basis of the simple linear regression model the predicted percent yield reductions at a seasonal mean concentration of 0.06 ppm compared to a 0.025 ppm control value were calculated as shown in the following table.*

*Also shown in this table are the predicted percent yield reductions which have been calculated at seasonal mean concentrations of ozone of 0.04 and 0.05, levels common to large areas of southern Ontario.*

| *Crop* | *Predicted % Yield Reduction at Seasonal* $O_3$ concentrations of:* | | |
|---|---|---|---|
| | *0.06 ppm* | *0.05 ppm* | *0.04 ppm* |
| *field corn* | *3.8* | *2.7* | *1.6* |
| *soybean* | *16.5* | *11.9* | *7.1* |
| *kidney bean* | *6.8* | *4.9* | *2.9* |
| *lettuce (head)* | *22.8* | *16.3* | *9.8* |
| *spinach (mean 4 var.)* | *19.6* | *14.0* | *8.4* |
| *turnip (mean 4 var.)* | *28.8* | *20.6* | *12.3* |
| *wheat (mean 4 var.)* | *11.0* | *7.8* | *4.7* |

** 7 hr/day growing season mean*

*In the second NCLAN report on field results (Kohut et al 1982), additional soybean yield data were generated from two sites using different seasonal mean ozone concentrations. At Ithaca, N.Y., Hodgson soybeans recorded yield losses of 8 and 20% at seasonal 7 hr mean concentrations of 0.035 and 0.06 ppm respectively, while at Beltsville Md. the losses for Essex and Williams soybeans were 15.7 and 6.3% at a seasonal 7 hr mean ozone concentration of 0.039 ppm.*

*Although the NCLAN project is the first nationally organized effort to determine yield losses in agronomic crops through the use of seasonally metered $O_3$ doses in open-top chambers there are, however, numerous reports of yield loss assessment studies using only the more simplified concept of ozone exclusion through charcoal filtered open-top chambers. In a 5 year study*

*in Maryland (1972-1979) typical annual yield reductions were 4, 9, 10, 17, and 20% respectively for field grown (under open-top chambers) snap beans, sweet corn, potatoes, tomatoes, and soybeans (Heggestad 1980). Although ozone levels were not recorded within the exposure chambers during the 5 year study period monitoring results at a near-by site (Beltsville) were provided by Heggestad et al (1980) and revealed that during the period from June through August hourly ozone values equalled or exceeded 0.10 ppm an average of 14 times per year.*

*In 1973, at Yonkers, New York (MacLean and Schneider 1976) the yield of snap beans and tomatoes grown in unfiltered open-top chambers was reduced by 26 and 33%, respectively compared to similar plants grown in carbon-filtered air. The average daily (0600-2100 EST) $O_3$ concentrations in the unfiltered chambers over the duration of the growth period (bean-43 days; tomato-99 days) were 0.041 and 0.035 ppm for bean and tomato, respectively.*

*In another study in Maryland, (Howell et al 1979) open-top chambers were used to assess the effects of airborne oxidants on four soybean varieties and demonstrated an average 20% loss in unfiltered compared to carbon filtered chambers. A similar loss (24%) was reported for Hodgson soybeans in Minnesota (Kohut et al 1977).*

## 3. EFFECTS OF POLLUTANT MIXTURES ON VEGETATION

*Rarely is plant life in nature exposed to the influence of only one air pollutant. Some controlled environment research has been conducted in which plants have been subjected to combinations of $O_3$ with, $SO_2$, $NO_2$ and simulated acid rain. The results of these experiments have been classified as additive*

*(equal to the sum of the effects of the individual pollutants), synergistic (greater than the additive effects), or antagonistic (less than the additive effects). In 1966, Menser and Heggestad reported that tobacco plants suffered 25 to 38% leaf damage upon exposure to a combination of 0.24 ppm $SO_2$ and 0.027 ppm $O_3$ for 2 hr, whereas either pollutant alone at approximately the same concentrations and for the same time period caused no injury. The leaf injury caused by the combination of the two gases resembled typical ozone injury. Heck (1968) reported that a combination of 0.10 ppm $SO_2$ and 0.03 ppm $O_3$ in a 4 hr exposure acted synergistically to cause injury to tobacco. Plants have been found to respond differently if the pollutant mixture regime is changed. For example, Tingey et al (1973) found that foliar injury on broccoli showed an additive response to a mixture of 0.25 ppm $SO_2$ and 0.10 ppm $O_3$ for 4 hr, whereas tobacco showed a synergistic response. However, if the regime was changed to 0.10 ppm $SO_2$ and 0.10 ppm $O_3$ for 4 hr the reverse occurred, with broccoli showing a synergistic response, and tobacco an additive response.*

*Experimental work has shown that low levels of $NO_2$ (0.10 ppm) in combination with $SO_2$ (0.10 ppm) injured five plant species in a 4 hr exposure period (Tingey et al 1971). The results were synergistic in that higher concentrations of each pollutant alone did not injure the same plant species.*

*Ozone combined with PAN caused an overall antagonistic response to pinto bean (Kohut and Davis, 1978). The plants were exposed to 0.30 ppm $O_3$ and 50 ppb PAN for 4 hr in which either pollutant caused specific symptoms, but together suppressed the PAN-type symptoms.*

*In preliminary experiments conducted in 1968, Heck reported that a mixture of three pollutants, $NO_2$, $SO_2$ and $O_3$ each at a concentration of 0.05 ppm injured tobacco plants. Reinert and Gray (1981) reported that radish growth was a sensitive measure of the effects of the three pollutants in combination. Radish plants were exposed to either 0.2 or 0.4 ppm of the three pollutants alone or in combination for periods of either 3 or 6 hours. $NO_2$ alone caused no visible injury, $SO_2$ alone caused trace injury at 0.4 ppm for 6 hr, whereas $O_3$ alone caused trace injury at 0.2 ppm for 6 hr. $NO_2 + O_3$ caused trace injury at 0.2 ppm for 3 hrs, with the injury resembling that caused by ozone alone. The exposure of radish plants to all three pollutants in combination caused greater than additive visible injury in comparison to the responses made by individual pollutants or by any two-pollutant combination.*

*There have been few experiments conducted to study the interaction between ozone and simulated acid rain. Jacobson et al (1980) demonstrated that ozone depressed the growth and yield of soybeans with three rain treatments (pH 2.8, 3.4 and 4.0), with the depression being greatest with the most acidic rain.*

*From the foregoing, it is apparent that the above experiments have demonstrated that low concentration pollutant combinations can adversely affect plant life. It is thus possible that certain plant effects observed in the field near point sources which have been attributed to individual pollutants may have been caused by pollutant interactions. However, in the agricultural areas of southern Ontario located at a distance from industrial sources, the prime atmospheric pollutant is $O_3$. On days with low $O_3$ concentrations, no air pollution injury has been observed to develop on crops, since other pollutants as $SO_2$ are present in negligible quantities.*

## 4. PROTECTION OF PLANT LIFE FROM OZONE DAMAGE

*The concept of mitigating plant injury through cultural methods, protective chemicals and genetically tolerant varieties is not new and has been thoroughly reviewed (Heck et al 1977; Ormrod and Adedipe 1974). In the area of cultural management, it has been found that plant response to $O_3$ can be slightly moderated by altering the mineral nutrition (nitrogen, potassium and sulphur) in the soil and by controlling the availability of water to the roots. However, unless the plants in question are being grown under controlled greenhouse conditions or in irrigated fields there is little or no possibility of utilizing these methods under normal agricultural field conditions. This applies also to other environmental factors (light, temperature, relative humidity) which are known to condition the response of plants to $O_3$ but which, in almost all cases, are beyond regulation under normal field conditions.*

*The use of protective chemicals also has been explored in numerous studies since the first report in 1954 of reduced oxidant injury to pinto beans through the use of several fungicides (Kendrick et al 1954). Since that time the list of chemicals which have been used is long but generally can be subdivided into two major groups - fungicides and antioxidants, and a third smaller group consisting of major growth regulators, vitamins, waxes, particulates and other chemicals. Of the two major groups fungicides have received the most attention with benomyl being the most widely studied because of its combined disease and oxidant protective properties and its suitability for use as a foliar spray, soil drench or soil amendment (Heck et al 1977). Other fungicides which have been examined include carboxin, zineb, maneb, thiram, ferbam, triarimol and dichlone. The effectiveness of some of these treatments with regard to protection against yield losses caused by $O_3$ has varied from about 40 to 100%*

*(Heck et al 1977) depending on the crop, the ozone dose, as well as the frequency of application and other environmental parameters.*

*The list of antioxidants which have been evaluated also is long and comprises simple reducing agents, commercial antioxidants, and specific antiozonants. The most promising chemical in this category was ethylene diurea (EDU) which was effective on many crop species either as a foliar spray or root application (Carnahan et al 1978). However, because of problems associated with the economics of development and residue testing EDU is no longer available from the manufacturer.*

*In their summation of protective chemicals, Heck et al (1977) outlined four major problems that have kept chemical protectants from practical use:*

1. *limited information on the frequency of application for effective protection and thus the cost of control*
2. *uncertainty regarding the specificity of selected chemicals on different plants*
3. *the lack of data on undesirable residues or side effects*

*and* 4. *the lack of predictive accuracy for high oxidant days for chemicals that are not persistent.*

*Problems in evaluating the effectiveness of the chemicals also have been encountered as crop growth improvement found in the laboratory or under controlled conditions is not always readily translated into controls to be expected in the field (Curtis et al 1975). On the basis of the work which has been conducted it would appear that any significant advances in this area will result from the assessment of ozone and disease interactions and the selection and application of existing pesticide chemicals that possess fungicidal as well as*

*antioxidant properties. This type of approach currently is under study for the potato industry of Ontario (Hofstra 1981).*

*Other alternatives for the reduction of $O_3$ related damage to crop plants are to develop genetic lines or varieties that have ozone tolerance or to avoid planting sensitive cultivars in high ozone impact areas. Genetic manipulation and selection has not been actively pursued although natural selection in most agricultural breeding programs probably has indirectly screened for those plants most tolerant to $O_3$. An example of this type of selection in a breeding program is evident in the tobacco research program at Delhi, Ontario, where weather fleck tolerance is considered in the development and recommendation of new flue-cured varieties (Pandeya et al 1982). Progress also is being made in Ontario on the development of both an ozone tolerant and high quality variety of white bean (Beversdorf and McKersie 1982).*

*The major problems in trying to avoid the use of sensitive crop varieties stem from a lack of current information on varietal response to ozone as research has not kept pace with the rapid introduction of new cultivars. Another problem is that the information, when it is available, most often deals with plant response (foliar injury) under specified $O_3$ dose exposures and in controlled plant growth chambers or greenhouses. These data have limited application in terms of crop yield potential under field conditions.*

*In summation, protection at the receptor level does offer some potential in reducing the impact of $O_3$ on the agricultural industry and thus warrants further evaluation. However, as is pointed out by Lokey et al (1979) these alternatives also involve certain costs which are associated with research, application and testing of chemical protectants, and changes in harvesting equipment.*

## 5. *OZONE MONITORING IN ONTARIO AND RELATIONSHIP WITH CROP DAMAGE*

*There have been limitations in assessing $O_3$ impact on crop species, in that a majority of $O_3$ monitors in both the U.S. and Canada were established in urban locations. They therefore may not represent levels to which rural vegetation is exposed. There also has been considerable variability in the manner in which $O_3$ results have been reported with previous methods including seasonal means, weekly means, 24 hour means, peak hourly means, number of hours above a given concentration, and percentage of time or number of hours above fixed concentration intervals (Heagle et al 1979b).*

*In Ontario the number of rural monitoring sites has increased from 2 in 1974 to 10 in 1981. Monitoring at a number of other rural sites also has been conducted during that interval but has since been terminated. The concept of a 7 hr per day, seasonal dose expression proposed by Heagle et al (1979) and further supported through the NCLAN project and EPA standard development techniques has been applied to all available Ontario and Eastern Canada (Nova Scotia, New Brunswick and Quebec) $O_3$ data.*

*Table 1 presents the Ontario seasonal (June-August) 7 hr per day (0900-1600 EST) $O_3$ values, the maximum 1 hr values, and the number of hours in excess of 0.08, 0.10 and 0.12 ppm $O_3$. The results have been partitioned into four regions of Ontario on the basis of the average seasonal 7 hr mean: Region 5 = 0.05 $\pm$ 0.005 ppm; Region 4 = 0.04 $\pm$ 0.005 ppm; Region 3 = 0.03 $\pm$ 0.005 ppm and Region 2: 0.02 $\pm$ 0.005 ppm. The geographical locations of the regions are presented in Figure 1. The trends in average seasonal 7 hr mean and average maximum 1 hr $O_3$ concentrations in Ontario from 1974 through 1981 have*

been graphed for all sites in Regions 5 and 4 and are shown in Figure 2. For comparative purposes the corresponding seasonal 7 hr $O_3$ means and the maximum 1 hr levels for Eastern Canada monitoring sites are shown in Table 2. The $O_3$ values for Quebec would fit Region 2 in Ontario, whereas the $O_3$ values for New Brunswick and Nova Scotia would more closely fit Region 3.

On the basis of these tables and figures it is apparent that the southern and central portions of the Province of Ontario are the most adversely affected by $O_3$ in Eastern Canada. This finding is corroborated by reports of $O_3$-related crop injuries in this area (Cole and Katz 1966; Curtis et al 1975; Linzon 1975; Hofstra et al 1978; Ormrod et al 1980) and by the absence of any documented injurious effects to sensitive agronomic or forest species in Quebec or the Maritime provinces.

It is further apparent that there has been only limited variation in the annual occurrence of seasonal 7 hr or maximum hourly $O_3$ means with a slight tendency for lower levels in the past 3 years (1979 to 1981). It is also very clear that Ontario's current 1 hr criterion of 0.08 ppm $O_3$ is frequently exceeded in regions with a seasonal 7 hr mean in excess of 0.03 ppm. In an effort to further explore the relationship between the maximum 1 hr $O_3$ value (24 hr/day: annual basis) and the corresponding 7 hr/day seasonal (June-August) mean, a statistical regression was run on the 173 data pairs (years x monitoring sites). The results of this analysis showing predicted seasonal means at a given 1 hr maximum value (criterion) are shown in Table 3.

It is apparent from this comparison that Ontario's current 1 hr $O_3$ criterion of 0.08 ppm if met would yield a seasonal 7 hr mean of 0.032 ppm. The

*relaxation of the criterion to a 1 hr maximum between 0.10 and 0.15 ppm (current U.S. standard = 0.12 ppm) would increase the seasonal 7 hr mean to values bordering on 0.04 ppm, a value common to all areas comprising Region 4 in Ontario (Fig. 1). Further, a relaxation to a 1 hr maximum between 0.16 and 0.20 ppm would yield a seasonal 7 hr mean of values bordering on 0.05 ppm, the value associated with all sites in Region 5 (Fig. 1).*

*A comparison of the above findings with those of Lokey et al (1979) reveals a considerable difference in the relationship between the 1 hr $O_3$ maximum and the associated seasonal 7 hr mean in Canada and the U.S. Although Lokey et al (1979) did not present a series of 1 hr - seasonal mean values they did equate a 1 hr maximum of 0.12 ppm with a seasonal mean of 0.06 ppm as compared to 0.039 ppm in Ontario. There are two possible explanations for this difference. First, the U.S. data used in the derivation of the relationship were entirely from urban areas with populations in excess of 200,000. The diurnal pattern (light-dependent) of $O_3$ formation in these areas would be fairly consistent as the precursors are continually being generated in a large urban complex. In contrast the Ontario data comprise both urban and rural sites which to a large extent are affected by meteorological conditions favourable to transport of $O_3$ and its precursors from industrialized areas to the south and southwest. As such there are many times during the season growing when $O_3$ levels are low, depressing the seasonal average.*

*The other discrepancy appears to arise from a slight difference in the time periods which were utilized in the averaging process. On the basis of the work by Heagle et al (1979) (1979b), Heagle and Heck (1980), and Heck et al (1982), the 7 hr seasonal mean was considered a biologically relevant dose in the period*

*from about 0900-1600 hr E.S.T. As reference was made in these papers to the relationship between the 0.12 ppm $O_3$ standard and the 0.06 ppm 7 hr seasonal mean as established by Lokey et al (1979) and as the NCLAN work was predicated on this basis it was decided that the Ontario data would be similarily averaged. However, in reviewing the work by Lokey et al 1979 it would appear that the seasonal 7 hr mean (0.06 ppm) was not calculated from data during the hours of 0900-1600 S.T. but was derived from the daily maximum 7 hr concentrations. If this is the case it would account for the higher U.S. seasonal mean as in both Ontario and the U.S. the diurnal trend in $O_3$ formation results in a 7 hr maximum between about 1200 and 1900 hrs (Barton and Rae 1978; Heagle et al 1979a).*

*In evaluating the U.S. NCLAN data and comparing their seasonal mean values with those in Ontario several key differences also must be recognized. The calculated NCLAN seasonal means are based on data during which time $O_3$ was metered into the chambers. This excludes days when, due to rain, $O_3$ was not added. Thus the reported seasonal mean values probably are higher than the corresponding results for Ontario where data for the low $O_3$, rainy days were included in the averaging process. Also contributing to a difference between the two mean figures is the period of exposure time. In the NCLAN work the duration of $O_3$ exposure was variable depending on the crop and usually was timed to coincide with the period of crop sensitivity. In some cases the plants were exposed throughout their entire life cycle while in others the exposure period was relatively short. In contrast, the seasonal means reported in Ontario are based on a three month period (June, July and August) which would cover the sensitive stage for most crop plants. Again this longer averaging time in Ontario tends to mask some of the short term, high mean*

*values that are experienced by averaging them with other periods during the growing season when $O_3$ levels were lower.*

*In view of these differences and considering the research projects and assessment studies which have been conducted in Ontario it is clear that identifiable crop damage can be associated with a seasonal 7 hr $O_3$ mean of 0.04 ppm and higher.*

## *6. OZONE EFFECTS ON ONTARIO VEGETATION*

*In Ontario the first indication of transboundary $O_3$ movement across Lake Erie was documented (Mukammal 1960) following extensive work on the relationship between the incidence of weather fleck on tobacco and meteorological conditions associated with the buildup of $O_3$. Since 1960 a number of large-scale meteorological investigations (Anlauf et al 1975; Yap and Chung 1977) have confirmed these early findings and have shown that high $O_3$ levels generally are associated with regional southerly air flows which have passed over numerous urban and industrialized areas of the U.S. and which, as they move across the lower Great Lakes, undergo rapid dispersion as they encounter unstable conditions near the northern shore of Lake Erie. Contributing to these influx patterns are the localized downwind urban effects which can add to the already high background levels.*

### *Agricultural Crops*

*In an effort to estimate the severity and extent of plant injury or yield loss resulting from exposure to ambient $O_3$ in Southern Ontario, a summary has been prepared for all major crop species on the basis of published research*

*reports of productivity losses in Ontario or the northeastern U.S. and on unpublished documents by government agencies or university departments. On the basis of these findings an estimated percentage loss (± 50%) for Ontario crops in each of Regions 4 and 5 where average seasonal means approximate or exceed 0.04 ppm has been derived and is shown in Table 4. These yield loss estimates formed the basis for the subsequent calculation of the monetary nature of the benefits to be derived from reducing $O_3$ concentrations.*

*Examples of the types of work which were considered in the assessment of crop yield losses for most of the 15 crops in Table 4 follow:*

*White bean*

*In 1961, bronzing and rusting of white bean foliage was reported (Clark and Wensley 1961) throughout southwestern Ontario and the resultant defoliation was estimated to have resulted in a loss of approximately 600 pounds of beans per acre (45% yield loss) in severely affected fields. Following extensive field work in 1965 and 1967 the disorder was found to be associated with the occurrence of elevated levels of atmospheric $O_3$ pollution (Weaver and Jackson 1968). The symptoms, which first appear sometime between flowering and normal plant senescence, a critical period in the development of yield potential, appear as a bronze-coloured necrotic stipple on the foliage which, as it becomes more severe, results in premature leaf drop and reduced seed set.*

*In an effort to assess and compare the annual severity of $O_3$ injury on sensitive white bean plants, Ministry of Environment (MOE) staff have conducted visual assessment surveys throughout the major production areas in southern and southwestern Ontario since 1971. In the 11 years of study over 330 visual ratings*

*of farm fields or experimental varietal plantings have been made with injury severity ranging from minimal amounts to severe bronzing and associated premature foliar loss (Pearson 1980). These annual visual surveys also ruled out any significant varietal resistance and confirmed that in any year the bronzing symptoms could appear throughout all bean production areas, with no particular pattern being apparent. The fact that the response of the white bean crop is so maturity dependent could, however, have masked any obvious severity pattern.*

*Experiments utilizing chemical protectants against $O_3$ injury have helped to provide information on yield losses related to the bronzing disorder in Ontario. In 1973 a 13% yield increase was associated with the reduction in bronzing severity (Curtis et al 1975), while in 1976, yield increases of up to 36% (27% yield reduction) were realized (Hofstra et al 1978).*

*In 1977 and 1978 white bean yield increases with antioxidant chemical protection were not as high (Toivonen et al 1980) due to climatic problems. The overall response in these years was 16 and 4% increase in yield respectively.*

*On the basis of these experimental values, the geographical location of the bean production areas (Regions 4 and 5) and considering the uniformity of cultivar sensitivity we have estimated the annual yield loss for all varieties of white bean crops in Ontario at 7 and 12% for Regions 4 and 5, respectively.*

*Potatoes*

*The foliar symptoms referred to as "speckle leaf" on this crop usually appear sometime after mid-July when the plant has flowered and the tubers are developing. As the demands for photosynthetically produced nutrition at this*

*time are at their peak the potential for adverse yield effects is considerable. The symptoms appear either as a blackened stipple or flecking on the upper leaf surface which can coalesce and become bifacial necrotic lesions or as undersurface, irregularly sized, silver-grey lesions which also can become bifacial as they increase in size and severity. Adding to the total impact of this injury are recent findings (Hofstra 1981; Bisessar 1981; and Holley 1982 (personal communication) which demonstrate that $O_3$ injury predisposes the plants to attack by the early blight disease organism thereby necessitating additional disease control treatments.*

*In Ontario, $O_3$-induced foliar symptoms have been observed as early as 1954 (Johnston 1972) and in several later years (McKeen et al 1973). On the basis of yield assessment studies conducted in Ontario and in the NE USA yield losses and tuber quality effects have been documented on several of the most sensitive processing varieties. Ontario Ministry of the Environment staff also have conducted annual foliar injury assessment surveys throughout the major potato production areas in Ontario since 1977 and in that time have examined over 130 plantings and recorded foliar injury development ranging from less than 1 and up to 30% leaf area (Pearson 1980).*

*On the basis of these findings, plus documented yield increases of potato in Ontario of 22 and 24% (Bisessar 1981; Hofstra 1981) respectively, with antioxidant and fungicidal protection, general reports of severe losses in the NE USA (Mosley et al 1978; Hooker et al 1973) and a documented 50% loss to a sensitive variety under greenhouse conditions (Heggestad 1973) we have estimated the annual yield losses for all varieties of potato crops in Ontario at 5 and 8% for Regions 4 and 5, respectively.*

*Other factors which may raise this estimate of loss in future years are the possible adverse effects on tuber quality (Pell et al 1980), the increased costs associated with additional disease control, and the fact that at least one agronomically important variety (Norland) can no longer be commercially grown due to extreme sensitivity to* $O_3$ *and high yield reduction effects.*

*Tobacco*

*'Weather fleck' of tobacco so named because of its relationship to certain weather conditions has been recognized as an* $O_3$ *induced foliar disorder in Ontario since 1954 (Cole and Katz 1966).*

*The symptoms appear on newly expanded leaves, the younger and older leaves of tobacco being more resistant. They start on the upper leaf surface as greyish, water soaked lesions which become light ivory to tan-brown in colour with time. In more severe episodes the lesions can coalesce into larger flecks or spots and become bifacial with increasing severity. Successive episodes of* $O_3$ *fumigation result in new lesions appearing on healthy tissues of recently injured, leaves as well as on newly expanded leaves higher on the main stem.*

*Although considerable success has been achieved in Ontario, in the area of breeding resistance into commercially acceptable tobacco varieties, yield losses associated with this high value crop continue to be a problem in tobacco production (Ormrod et al 1980; Watson and Sheidow 1982). In 1972 and 1973, decreased leaf weight and quality (0.73%) were calculated by Gayed and Watson, 1975, while estimates of tobacco crop loss for the years from 1975-1981 have varied from 0.2 - 2.5% (Watson and Sheidow 1982). A visual assessment of foliar injury severity consisting of 33 separate observations throughout the major*

*tobacco production areas of southern Ontario in 1977 by Ontario MOE staff confirmed the presence of foliar injury development ranging from less than 1 and up to 20% on flue-cured tobacco species (Pearson 1980). In view of the above findings we have estimated the production losses for all varieties of tobacco crops in Ontario at 0.6 and 1.0% for Regions 4 and 5, respectively.*

*Tomato*

*Although tomato is an $O_3$ sensitive crop species and has been investigated for varietal sensitivity (based on foliar injury) by a number of researchers, typical injury symptoms have seldom been reported in the field in Ontario (Legassicke and Ormrod 1981). There are, however, numerous reports which document the adverse effect on tomato yield due to ambient (MacLean and Schneider 1976) (Oshima et al 1977) or controlled (Henderson and Reinert 1979) oxidant exposure.*

*In North Carolina (Henderson and Reinert 1979) early marketable yield of some tomato varieties was significantly reduced by exposure of the plants to $O_3$ prior to their establishment in the field. In spite of the fact that the final total yield was not affected, an economic loss was predicted based on the price differential between the early and late season markets. In the New York study, MacLean and Schneider (1976) documented a 33% yield reduction effect for plants grown in unfiltered chambers relative to charcoal filtered chambers. The average day-time seasonal mean in the unfiltered chamber over the duration of this experiment was 0.035 ppm $O_3$.*

*In Ontario there are two reports citing an adverse effect of $O_3$ on tomato yield. In one (Legassicke and Ormrod 1981) a yield reduction of 24% was*

recorded for one variety compared to tomato plants afforded chemical protection. In the other study, which is still in progress, Ormrod (1981) has so far found a reduction of 8% in tomato yield for several varieties at several locations. Although many of the varietal comparisons were not significant there were some that approached 30% yield reduction.

On the basis of these yield loss findings, the lack of visible symptoms in Ontario, and the documented varietal response of this plant, we have estimated the annual yield loss for all varieties of tomato crops in Ontario at 2 and 5% for Regions 4 and 5, respectively.

Onion

Onion leaf dieback and flecking have been attributed to a number of parasitic and non-parasitic agents since the first report of the disorder in Wisconsin in 1903 (Whetzel 1904). More recently the search for the causal agent in the tipburn or blast syndrome has centered on atmospheric $O_3$. Engle et al (1965) found a close relationship existed between the presence of flecking and tipburn in onions and high levels of $O_3$. Engle and Gabelman (1966) later published on the genetic resistance of certain varieties of onions to $O_3$ exposure.

In Ontario Wukasch and Hofstra (1977a) (1977b) examined the effect of $O_3$ exclusion and chemical protection on the yields of field grown onions. They documented 22 and 28% yield reductions in non-filtered compared to charcoal filtered chambers, and a 28% reduction in plants compared to those provided with an antiozonant protectant.

*On the basis of these yield studies, the documented variation in cultivar sensitivity and considering the fact that $O_3$ injury was shown to predispose onion plants to more severe Botrytis infection (Wukasch and Hofstra 1977b) we have estimated an annual yield loss for all varieties of onions in Ontario of 5 and 8% in Regions 4 and 5, respectively.*

*Grapes*

*Dark brown to black spotting or stipple of grape leaves was first reported in California (Richards et al 1958) and was attributed to the presence of atmospheric $O_3$ in the grape production areas. The symptoms, which include premature leaf senescence and abscission and are commonly called "brown leaf disorder" have been reported to be widespread on several American cultivars and French hybrids grown in vineyards throughout upper New York State (Shaulis et al 1972). In 1973 and 1974 (Kender and Carpenter 1974), a large number of grape cultivars and hybrids in both New York State and Ontario were assessed for oxidant injury severity and these findings prompted a four year Ontario study to ascertain the extent of the problem in terms of the severity of foliar injury development and potential adverse effects on crop yield and quality. These results (Ormrod 1979) confirmed that the 'brown leaf' disorder of grapes is a readily recognizable problem in Ontario each year. The failure of the anti-ozonant chemical treatment to offer sufficient protection from foliar injury development negated the efforts to quantify any adverse yield and quality effects. Adverse yield and quality effects were, however, demonstrated in a California study (Thompson and Kats 1970) using Zinfandel grapes in field studies with protection by charcoal filtered chambers. On the basis of these findings we have estimated that the yield loss to all varieties of grape crops in Ontario probably is confined to Region 5 and is a minimal 3%.*

*Cucumbers*

*Chlorotic mottle of leaves, early leaf senescence, and, possibly increased susceptibility to diseases are problems incurred by cucurbit species in southern Ontario each year due to oxidant exposure (Ormrod 1980). In 1979 and 1980 studies were undertaken to assess the relationship between foliar symptom development and yield suppression in cucumber. The studies utilized a number of different locations using two different chemical protectants. The results (Ormrod 1980; Ormrod 1981) revealed that at some locations there was a varietal response to chemical protection. The results in 1979 were less conclusive than those of 1980 when overall reductions of 13% were recorded, with one location (all varieties) yielding 15% less in unprotected cucumber plots compared to those provided with antioxidant protection.*

*On the basis of these findings and the fact that the research was conducted during two years when $O_3$ levels were low, we have estimated that the yield loss associated with all varieties of cucumber crop in Ontario is 2 and 5% in Regions 4 and 5, respectively.*

*Other Sensitive Crops*

*Although adverse $O_3$ effects on productivity of certain other crops have not been documented in Ontario there have been a number of studies conducted in the NE USA which indicate the potential for growth and yield losses for the following crops: green beans, lettuce, radish, rutabaga, soybean, spinach, sweet corn and wheat.*

*In a five year study at Beltsville, Md. (Heggestad et al 1980) yield losses in a snap bean cultivar ranged from 5-27% in non-filtered air compared to charcoal*

*filtered air. In another case a yield reduction of 22% was recorded. In Massachusetts (Manning et al 1974) a significant yield reduction (29%) was observed with Tempo, the most sensitive snap bean variety to oxidant injury. In 1970 at Raleigh, North Carolina (Heagle et al 1972) a sensitive sweet corn variety exhibited a 30% reduction in ear weight following exposure to long term low levels of $O_3$ in a non-filtered chamber.*

*Reductions which have been documented in the USA for the other crops have been previously referenced in the section describing the NCLAN project. In all cases, the predicted crop yield loss estimates for Regions 4 and 5 (Table 4) are based on the degree of varietial reponse reported, and the relationship between the yield reduction and the seasonal mean $O_3$ level reported in the respective studies.*

## *Forests*

*There are many different parameters and limiting factors which must be considered in evaluating and quantifying the effects of $O_3$ on forest trees as compared to agricultural crops. Forest tree species are long-lived, perennial plants that are exposed to $O_3$ repeatedly during the year and over several years and, unlike agricultural crops, are not usually subjected to fertilization, irrigation and, pesticide application or other cultural practices that can moderate their response in the field. Assessment of adverse effects of $O_3$ on seedlings or young trees can be evaluated under controlled conditions. However, the large size of trees at maturity precludes experimental pollutant exclusion (chamber) studies or the use of protective antioxidant sprays which limit the assessment of yield losses to visual observations of foliar injury, and radial and height growth characteristics of individual trees in the stand. Where growth*

*analysis is undertaken from different stands on the basis of air quality gradients, the data must then be considered in terms of edaphic and climatic site variation and related to $O_3$ dose information, where available. Another complicating factor which must be addressed when assessing the overall impact of $O_3$ on forest growth and yield is the process of inter-plant species competition and possible alterations in successional processes and species composition. In this regard an adverse effect on the growth or survival of one tree species could have either a beneficial or detrimental effect on the growth or survival of another species thereby increasing or decreasing the total productivity of a mixed forest stand. However, as indicated by Treshow (1970) ecosystems usually are delicately balanced with a structure which may depend on a few critical species and any disruption in this balance after prolonged environmental stress could, therefore, lead to very rapid, irreversible changes.*

*On the basis of artificial $O_3$ fumigation exposures, many tree species indigenous to Eastern North America are classified as being susceptible to foliar $O_3$ injury (Davis and Wood 1972; Davis and Coppolino 1974; Davis and Wilhour 1976; Skelly 1980). Direct injury to tree foliage by $O_3$ has been demonstrated repeatedly in experimental situations, and in nature as well. Concentrations of $O_3$, at least in some forested areas, are sufficient to cause injury (Linzon 1973; Miller and McBride 1975; Skelly 1980). As indicated, these $O_3$ effects can alter the productivity, successional patterns, and species composition of forests (Smith 1980) and enhance activity of insect pests and some diseases (Woodwell 1970). The current status concerning ozone-induced effects on Temperate and Mediterranean forest tree species, communities and ecosystems has been summarized by Skelly (1980) who concludes it is possible that primary productivity, energy resource flow patterns, biogeochemical patterns and species*

*successional patterns may all be challenged by oxidant air pollution.*

*In Ontario foliar symptoms associated with $O_3$ injury to white ash and Eastern white pine have been observed by MOE staff extensively throughout Regions 5 and 4 and occasionally in Region 3. (Fig. 1) Skelly et al (1982) reported decreases in height growth of several tree species, including eastern white pine, Virginia pine, eastern hemlock and green ash, in Virginia compared to the same tree species growing in charcoal-filtered chambers. There was about a 10% reduction in growth per year in ambient air with the monthly average $O_3$ concentrations ranging from 0.04 to 0.065 ppm. Photochemical oxidants (mainly $O_3$) have caused severe effects on ponderosa pine and white fir forests in California, with significant reductions in radial growth increment having been measured (Ohmart and Williams, 1979). There are, however, no available studies which quantify the severity of the oxidant foliar symptoms relative to the total annual yield of these or other tree species. The one advantage which is enjoyed by Ontario's forest industry is the fact that $O_3$ levels generally decrease in a south to north direction (Fig. 1) and thus are lowest in the areas where forests predominate. For this reason forest yield losses due to ambient $O_3$ in northern Ontario would be considered to be low when compared to the yield losses which have been measured in the agricultural areas in southern Ontario.*

*Ornamentals*

*There have been a number of experimental studies designed to examine the effect of $O_3$ on woody and herbaceous ornamental plants. Some of the species examined include: petunia (Craker 1972), carnation (Feder and Campbell 1968; Feder 1970) geranium (Feder 1970), poinsettia (Manning et al 1973),*

chrysanthemum (Klingaman and Link 1975; Brennan and Leone 1972), begonia, coleus, snapdragon, marigold, celosia, impatiens, salvia (Adedipe et al 1972), tree-of-heaven (Davis and Coppolino 1974) and lilac (Hibben and Taylor 1974). The results of these studies have shown a considerable degree of varietal sensitivity with effects ranging from growth depression, alteration of plant habit, retardation of floral initiation as well as reductions in flower production. However, as most of the studies have been varietal screening tests using relatively high concentrations of $O_3$ with short exposure periods there has not been any attempt to quantify the productivity implications. However, further studies should be conducted on the growth and yield effects of $O_3$ on ornamentals because most of the nurseries in Ontario are located in the southern portion of the province where highest $O_3$ levels occur.

## 7. ESTIMATES OF SELECTED ECONOMIC BENEFITS DUE TO REDUCTION IN OZONE CONCENTRATIONS

Ozone can have a number of different detrimental effects including vegetation damage, materials damage and, possibly increased incidence of disease or mortality. The focus of this assessment will be, however, the biophysical effects of $O_3$ on vegetation and the economic consequences of reducing vegetation damages.

There are three types of economically important terrestrial vegetation in Ontario: agricultural crops, forests and ornamentals. This evaluation will be concerned only with agricultural crops for the following reasons. First, the dose-response relationships between ambient $O_3$ concentrations and yield effects on economically important tree species are not well known. Second, much of Ontario's commercially harvestable timber grows in the north where $O_3$

*concentrations are low and there is little likelihood of damage. In contrast, much of the agricultural production in this province takes place in southern Ontario where $O_3$ concentrations are high relative to background levels. Finally, inventory data on ornamental plants, as well as dose-yield response information on these species, are unavailable.*

*Estimates of the dollar value of crop "losses" due to $O_3$ in the U.S. have been published since 1963 (Jacobson, 1982). These estimates have been made by experimentally determining the percentage by which crop production could be increased by reducing ambient $O_3$ levels to specified background concentrations. The economic value of what is assumed to be the annual "lost production" is obtained by multiplying this percentage by the total market value of the crop in question for a particular year. Heagle and Heck (1980) and Heck (1981) describe and report on the results of this approach.*

*Based on this approach, Heck (1981, p. 5) states that:*

> *"It seems reasonable to assume that, if all areas of the United States were meeting the current $O_3$ standard (0.12 ppm for 1 hr), the losses to crop production would be between 1 and $2 billion or from 2 to 4% of total production".*

*This approach does not yield meaningful estimates for policy deliberations for several reasons. First of all, the relevant estimates for policy evaluations are the value of damages avoided if $O_3$ concentrations were reduced to the standard, not the value of damages occurring at the standard. Estimates should be made of the crop production increases that result from $O_3$ reductions so that the consequences should be called benefits. Moreover, the dollar value*

*estimates cited by Heagle and Heck are based on market prices that are derived from the production of crops under prevailing $O_3$ conditions. If crop production were to increase, prices for many crops could be reduced so that the total value of the extra production would be altered accordingly. Finally, this approach is devoid of any information about the relevant production processes and markets so that one cannot judge whether the estimates overstate or understate the true values. In addition, it is not possible to determine how these effects are distributed among regions, farmers and consumers of agricultural products.*

*The procedure described below will yield more comprehensive and meaningful estimates of the economic value of crop production increases resulting from reductions in $O_3$ concentrations. An important aspect of this approach is to explicitly calculate the changes in crop production in their relevant, biophysical units. This will permit the reader to apply his own value weighting measures (e.g. prices) if he wishes.*

*Methodology*

*Zones of ambient seasonal 7 hr mean $O_3$ concentrations in Ontario are presented in Figure 1. At the average levels in "Ozone Regions" 4 and 5, 0.04 and 0.05 ppm $O_3$ respectively, damage has been observed on some agricultural crops. This damage is expressed as a reduction or loss in the yield of each crop from what it could be at ambient $O_3$ concentrations of 0.03 ppm or less. The estimated percentage loss in yield of each relevant crop is listed in Table 4.*

*Therefore, a benefit of control actions that reduce $O_3$ concentrations*

will be the increase in crop yield that could result. Each crop has a different sensitivity to $O_3$; in other words, the extra yield that could result from a reduction in $O_3$ concentration will differ from crop to crop.

Calculations of the extra yield that could result if $O_3$ were reduced from 0.05 to 0.03 ppm 7 hr seasonal mean and from 0.04 to 0.03 ppm or lower are summarized in Table 5. The ranges of this potential extra production are presented as well. For example, in areas where $O_3$ concentration averages about 0.05 ppm (Region 5) the yield of white beans could be increased by about 14% if concentrations were reduced to 0.03 ppm or lower, with a possible range of between 6 to 22%.

The economic significance of these potential crop increases is measured in part by the monetary value of the extra production that is afforded by the reduction in $O_3$ levels. In addition to how much these benefits are worth, it is also important to determine who (in terms of groups and/or locations) will in fact, gain from the consequences of the $O_3$ control actions.

The procedure to estimate these biophysical and economic effects is summarized as follows:

1. Determine the locations and the yield loss of various crops that are exposed to damage-causing levels of $O_3$ (e.g. above 0.03 ppm 7 hr seasonal mean). This information is presented in Figure 1 and in Table 4.

2. Identify any mitigative actions such as resistant cultivars and

*antioxidant chemicals that have been implemented to offset damages which impose extra costs on producers.*

3. *Based on dose-response information (Table 4), calculate the total amount of production increases that could result from a lowering of $O_3$ concentrations, or the production decreases that could result from increases in $O_3$ levels. The production increase relationships are indicated in Table 5.*

4. *To obtain an estimate of the monetary value of the production change, multiply the amount of change by the appropriate market price. However, if production increases or decreases are large relative to the entire market for the product in question, then the market prices of the crop could decrease or increase and one should use the new price to estimate the monetary value of the change in production.*

5. *To obtain the economic benefit to producers (farmers) of the reduction in $O_3$ levels, multiply the change in crop production by the appropriate price and subtract any extra costs that might be incurred in growing, harvesting or transporting this extra production. This profit to farmers is a part of the benefit of the oxidant control.*

6. *Add to this profit any decrease in costs that might result if cultural practices currently being taken by growers (extra fertility, sprays etc.) can be reduced or eliminated.*

7. *If prices of the crops are lowered because of the production increase*

*(or raised because of production losses) consumers will also experience a net gain or loss in terms of their willingness to pay. This quantity must be calculated by obtaining estimates of the demand functions for each crop. Demand functions indicate the amounts of money that people are willing to pay (per unit of product) at different levels of consumption. If prices decline, many people are then able to pay less than they would be willing to pay for the products in question and so they experience a monetary benefit or gain. The benefit consumers would experience (or the cost they would incur if prices were increased) is called Consumer's Surplus.*

*Adams, et al (1982) have compared the results obtained from the "traditional" approach of multiplying the change in crop production by the appropriate market price with a more theoretically satisfactory and comprehensive methodology involving an econometric assessment of price changes on consumer surplus. The effects of increased $O_3$ levels on four agricultural areas in Central and Southern California were studied. In addition to showing the distribution of damages or benefits between producers and consumers of changes in $O_3$ levels, the results of this study indicated that damage estimates based on the comprehensive econometric procedure were lower than those based on the "traditional" approach. It is not clear whether this result would necessarily extend to other situations.*

*Market Conditions for Crops at Risk*

*It is necessary, therefore, to determine whether the potential production increases for each of the crops considered in Ontario will have any effect on market prices. An assessment of the market structure of each crop is necessary*

to determine whether there might be any price effects.

Such an assessment of each of the crops listed in Table 4 was undertaken by economists at the Ministry of Agriculture and Food (Crozier, personal communication). It was concluded that, due to the magnitude of the crop production increases relative to total production quantities and to the market structure (i.e the prevalence of Marketing Boards and supply management activities) of each crop, market prices would not change if production increases of the magnitudes envisioned in Table 5 were realized. Consequently, there would be no additional benefits in terms of lower prices and consumer's surplus to consumers of agricultural crops associated with oxidant decreases in Ontario. Furthermore, the monetary value of the crop production increases could thus be calculated using current market prices.

Finally, it was concluded also that costs associated with shifting the location of particularly sensitive crops such as white beans, was negligible.

Agronomists and crop specialists in the Ontario Ministry of Agriculture and Food and the Ministry of the Environment also concluded that any extra costs associated with the increased crop production would be negligible in each case. Consequently, the profit to producers (farmers) is equal to the total revenue associated with the extra crop production using current, invariant market prices.

*Calculation of the Monetary Benefits of Ozone Concentration Reductions*

The extra production for each crop listed in Table 5 was calculated in the following manner. First, those areas where $O_3$ concentrations are above 0.04 ppm (Regions 4 and 5 in Figure 1) and currently suffering $O_3$ damage would

benefit for the most part from $O_3$ reductions. Next, the average annual crop production for three years, 1978-1980, was calculated. Then, the potential increase in production for each crop was estimated by noting that actual production has, in fact, been reduced from some total potential output.

The change in production is, therefore, equal to the difference between this Potential Production ($P_p$) and the Current Production ($P_c$). Since only the % Loss (% L) and Current Production are known, the potential increase in production ( $\Delta$ P) can be estimated from equations (1) and (2).

$$P = P_p - P_c \qquad (1)$$

where

$$P_p = \frac{P_c}{100\%-\%L}$$

Therefore

$$\Delta P = \frac{P_c}{100\%-\%L} - P_c \qquad (2)$$

A more operational formula can be derived from equation (2). By rearranging terms,

$$\Delta P = \frac{P_c \times \%L}{100\%-\%L} \qquad (3)$$

Equation (3) was used to calculate potential production increases for Regions 4 and 5.

*Results of these calculations are presented in Table 5. All results are expressed in metric tonnes. Calculations of production increases using the "high" and "low" % yield loss values are made as well.*

*Prices used to calculate increased profits to producers are the average of unit value for each crop over the years 1978-1980, expressed in $ per metric tonne. Current, not constant, unit values or prices are used.*

*The dollar value calculations of the increased crop production are summarized in Table 6 for each crop in Regions 4 and 5. These values are on an annual basis.*

*Based on the dose-response relationships presented in Table 4, the monetary value of the extra crop production that could result from reducing* $O_3$ *concentrations in Regions 4 and 5 to 0.03 ppm or lower (7 hr seasonal mean) would be about $15 million per year with a range between 9 to $23 million.*

*Several qualifications should be made concerning these estimates. First, they may be overstated somewhat if there are, in fact, extra costs associated with the extra production. Any such costs should be subtracted from these totals. Second, these are estimates for one year in "current" dollars, not adjusted for inflation. If these estimates are to be compared with estimates of the costs of oxidant control measures that will require several years to put in place, then these monetary benefit estimates will have to be aggregated over a specific number of years and appropriate discounting procedures applied.*

Finally, total production of the crops examined in this paper, as well as their respective market prices, vary considerably from year to year according to weather, changes in cropping plans, foreign demand and other reasons. Economists in the Ministry of Agriculture and Food have indicated that no reliable forecasts of future crop production or market prices are available. Consequently, the estimates presented here are valuable as an indication of orders of magnitude, not as precise estimates or forecasts of benefits.

It should be stressed that these estimates are not at all comparable with those of Heagle and Heck (1980) or Heck (1981).

More comparable estimates are, however, being developed. Moskowitz et al. (1982) report on a comprehensive model that can be used to estimate potential crop production increases and their value at the county level. In addition, more reliable dose-response functions for various crops are being developed under the auspices of the U. S. NCLAN program (Heck et al 1982).

## Implications of the Results

The estimates in Table 6 are listed in order of the magnitude of the estimated dollar value of benefit. Five crops; soybeans, potatoes, tobacco, white beans and wheat, account for more than 80% of the total value of the benefit of $O_3$ reduction in the entire province. Moreover, about 70% of the potential benefits would occur in Ozone Region 5.

Information on the likelihood or probabilities associated with the potential

*crop increases would be helpful in further evaluating these benefit estimates against the costs of oxidant control. Estimates of these probabilities could be based on the probabilities of $O_3$ concentration reductions resulting from oxidant control measures.*

*Finally, without estimates of the costs of achieving reductions in $O_3$ concentrations, one can say little about the social desirability of implementing these reductions.*

### *Further Work*

*This set of estimates assumed that $O_3$ concentrations will be reduced in all areas of the province to 0.03 ppm (7 hr seasonal mean). Consequently, the value of the benefits from reduced agricultural damages presented in this paper represent a maximum that could be achieved. Several other scenarios are possible and may in fact be more likely. For example, if most of the oxidants in southwestern Ontario are found to be transported from the U.S., control efforts in Ontario may not be able to reduce $O_3$ concentrations in the agricultural areas of the Province. Efforts and programs in Ontario may acutally reduce $O_3$ concentrations only in urban areas, such as Toronto or Sarnia or in the $O_3$ bulges immediately northeast of these cities.*

*Various $O_3$ reduction scenarios can be postulated and the benefits estimated. For example, controls may result in $O_3$ concentrations to 0.04 ppm rather than 0.03 ppm. However, estimates of oxidant control technologies costs and their results in terms of reduced $O_3$ concentrations should be developed before any further estimates can be made.*

## 8. CONCLUSIONS

In the foregoing sections of this report the effects of $O_3$ on vegetation, materials, visibility and human health are discussed. Materials are being affected by ambient levels of atmospheric $O_3$, and a decrease in visibility occurs under a combination of high oxidant levels and adverse meteorological conditions. The effects of $O_3$ on human health are based primarily on controlled exposure studies, with little work having been done epidemiologically. Recent research indicates a threshold level of 0.10 ppm $O_3$ for children and 0.12 ppm for adults. Thus there is no margin of safety between demonstrated effects and the current U.S. standard for $O_3$ of 0.12 ppm for 1 hr. The Ontario criterion and Canadian objective for $O_3$ is 0.08 ppm for 1 hr and, as described earlier in this report, severe crop damage is occurring both in the U.S. and Ontario because this $O_3$ dose is frequently being exceeded.

In southern Ontario atmospheric $O_3$ levels infrequently exceed 0.12 ppm/1 hr but often exceed 0.08 ppm/1 hr with agricultural crops annually experiencing foliar damage and associated yield losses. At three rural sites in southwestern Ontario during the period 1978 to 1981, there was an average of only 7 days during each year that the maximum hourly $O_3$ concentration exceeded 0.12 ppm. (See previous chapter). If the Ontario criterion were relaxed to 0.12 ppm/1 hr, the number of days with hourly $O_3$ concentrations exceeding 0.08 ppm would be expected to increase, resulting in even greater crop losses. Conversely, if oxidant control efforts were taken both in the U.S. and Ontario to meet the criterion of 0.08 ppm/1 hr in all areas of Ontario, crop production would increase since $O_3$ damage would be virtually eliminated.

Visible injury has been observed on plant foliage exposed to $O_3$ concentrations of 0.08 ppm for 1 hr, with more severe injury occurring at higher concentrations and over longer periods of time. Whether this direct visible injury has an immediate response on overall plant productivity is not certain in all cases. Crop yield losses have been measured without the presence of visible injury, and conversely, visible injury has not, in all cases, been associated with decreased productivity. One cannot generalize in this respect, but in the majority of instances, decreased growth and yield of plants have been associated with visible injuries on the foliage.

Regardless, the most important $O_3$ dose with respect to final plant yield at harvest is the average concentration that the crop is exposed to over the entire growing season. Certainly, individual high concentration $O_3$ doses are important, but an actual measure of yield loss related to an individual exposure would be difficult, if not impossible to determine. However, the daily average $O_3$ concentration for a fixed time period (e.g. 0900 to 1600 hr EST) over the entire growing season had been selected by the U.S. NCLAN program as the best biologically relevant parameter to correlate with yields of crops. Using this 7 hr seasonal mean for $O_3$ it has been found both in the U.S. and in Ontario that an average of 0.04 ppm can result in significant yield losses in sensitive crops, such as soybean and white bean. Higher 7 hr seasonal means of 0.05 ppm and over have resulted in correspondingly greater crop losses.

In Ontario, it has been found that if levels of $O_3$ are maintained at 0.03 ppm (7 hr seasonal mean) little or no $O_3$ injury or damage to crops will occur. It has been calculated statistically from 8 years of Ontario monitoring data that an

*annual maximum concentration of 0.08 ppm $O_3$ for 1 hr corresponds to a 7 hr seasonal mean of 0.032 ppm. However, it has been shown that $O_3$ levels in much of southern Ontario exceeds this criterion. If control efforts could achieve reductions in the average $O_3$ concentrations to meet the 0.08 ppm/1 hr criterion (or 0.032 ppm/7hr/seasonal mean) in all sections of the Province, the value of the extra crop production to farmers could amount to as much as $23 million per year with a more likely average of about $15 million per year (in 1980 $).*

*In order to assess the implications of additional oxidant control programs for policy purposes, the costs of these programs must be estimated. If the annual costs of achieving the 0.08 ppm criterion are substantially higher than the estimated value of the increased crop production, it would be advisable to examine and estimate in greater detail the reductions in material damages and human health effects that would be associated with $O_3$ reduction.*

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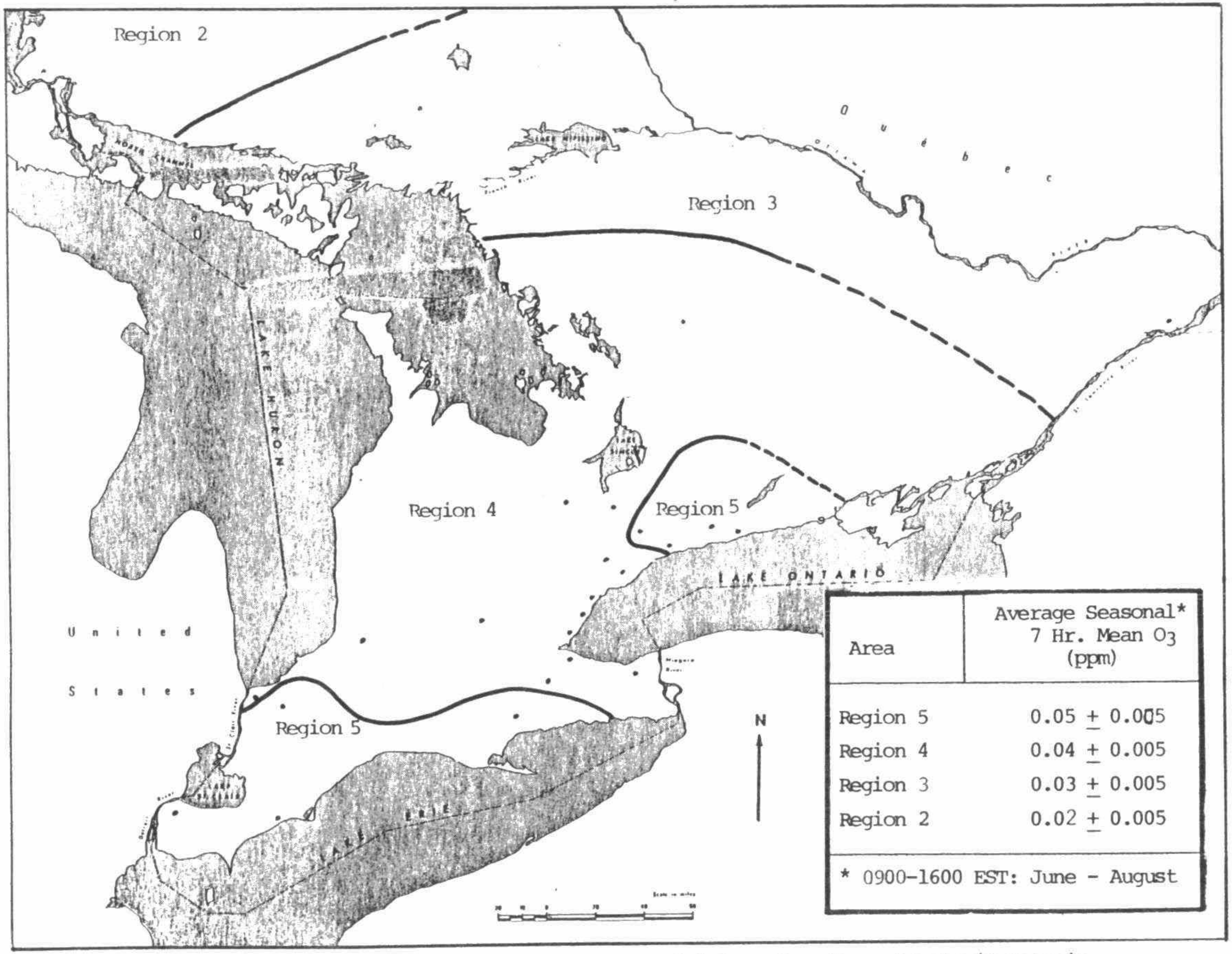


Figure 1. Regional Contours of Average Seasonal 7 Hour Mean Ozone Levels in Ontario

Figure 2 - Trend in Seasonal Mean and Maximum Ozone Concentrations in Ontario 1974-1981

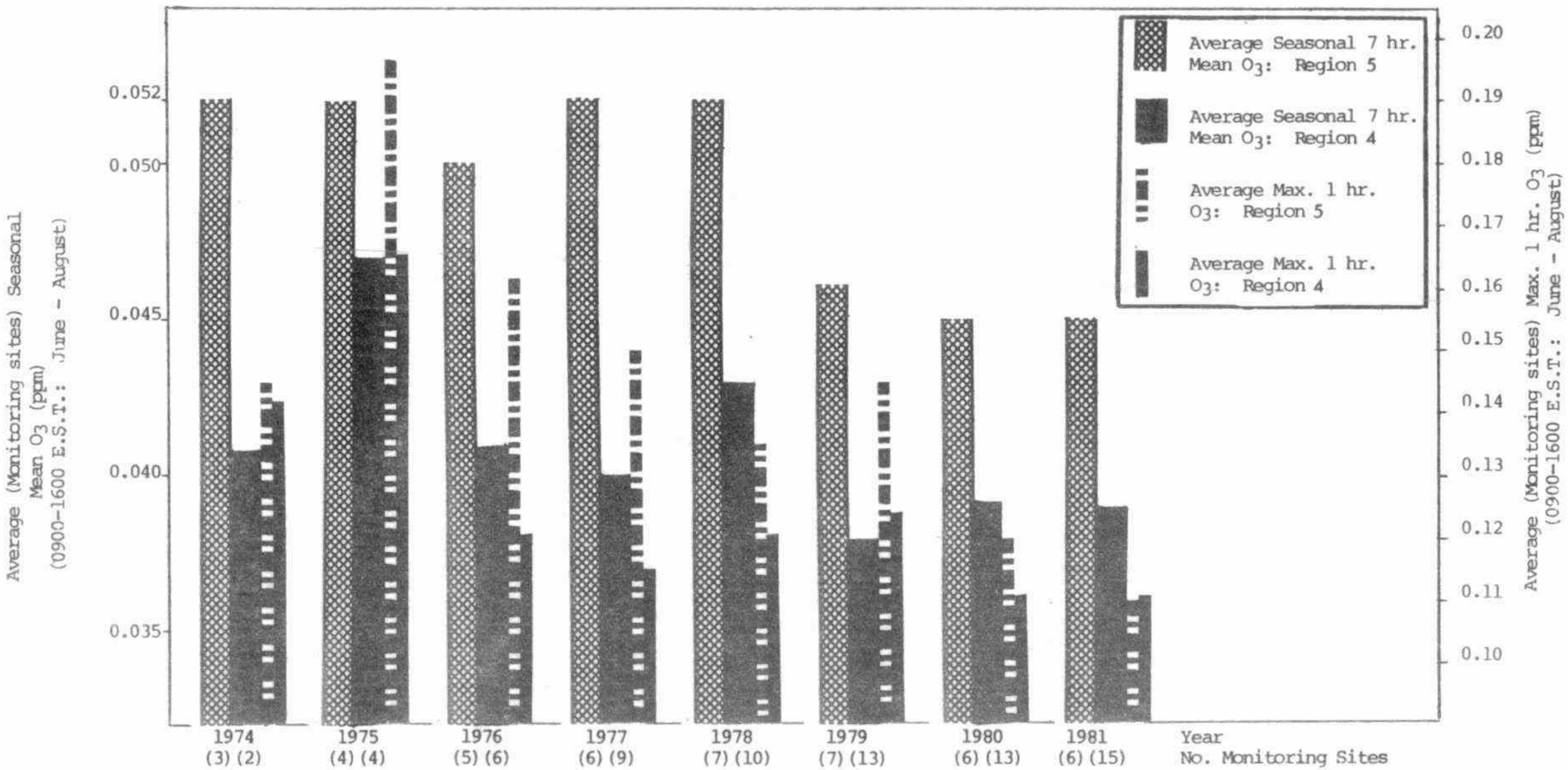

***Table 1. Summary of Growing Season (June, July, August) $O_3$ Data for Ontario: 1974-1981.***

| Location | U=Urban R=Rural | No. Years Monitored | All values Based on Hourly $O_3$ Data from 0900 to 1600 E.S.T. (7 hr/day) during June, July, August | | | | |
|---|---|---|---|---|---|---|---|
| | | | Ave*. Max. 1 hr $O_3$ (parts per million) | Ave*. Seasonal 7 hr Mean $O_3$ (parts per million) | Ave. No. Hrs $O_3$ > 0.08 | 0.10 | 0.12 |
| - Region 5 (Seasonal Mean = 0.05 ± 0.005 ppm) - | | | | | | | |
| Windsor | (U) | 8 | 0.147 | 0.046 | 64 | 18 | 5 |
| Petrolia | (R) | 5 | 0.137 | 0.046 | 55 | 15 | 4 |
| Merlin | (R) | 5 | 0.134 | 0.048 | 45 | 13 | 4 |
| Long Point | (R) | 3 | 0.127 | 0.054 | 45 | 10 | 1 |
| Simcoe | (R) | 8 | 0.122 | 0.053 | 57 | 14 | 2 |
| Stouffville | (R) | 7 | 0.143 | 0.047 | 56 | 21 | 12 |
| Orono | (R) | 5 | 0.167 | 0.049 | 78 | 32 | 10 |
| Wesleyville | (R) | 3 | 0.177 | 0.052 | 97 | 35 | 9 |
| - Region 4 (Seasonal Mean = 0.04 ± 0.005 ppm) - | | | | | | | |
| Sarnia | (U) | 8 | 0.153 | 0.043 | 38 | 13 | 4 |
| Tiverton | (R) | 3 | 0.118 | 0.040 | 22 | 6 | 1 |
| Huron Park | (R) | 5 | 0.117 | 0.044 | 38 | 6 | 1 |
| London | (U) | 7 | 0.113 | 0.041 | 31 | 4 | 1 |
| Kitchener | (U) | 5 | 0.103 | 0.041 | 34 | 4 | 1 |
| Tyneside | (R) | 3 | 0.106 | 0.042 | 12 | 1 | 0 |
| Alliston | (R) | 1 | 0.099 | 0.040 | 9 | 0 | 0 |
| Burlington | (U) | 3 | 0.114 | 0.037 | 17 | 7 | 1 |
| Hamilton | (U) | 7 | 0.115 | 0.036 | 33 | 9 | 2 |
| Oakville | (U) | 6 | 0.119 | 0.044 | 31 | 8 | 1 |
| Mississauga | (U) | 4 | 0.112 | 0.037 | 19 | 3 | 1 |
| Holland Marsh | (R) | 3 | 0.111 | 0.042 | 31 | 6 | 0 |
| Toronto** | (U) | 7 | 0.120 | 0.036 | 32 | 10 | 3 |
| Oshawa | (U) | 3 | 0.141 | 0.037 | 28 | 7 | 2 |
| Dorset | (R) | 1 | 0.084 | 0.036 | 1 | 0 | 0 |
| - Region 3 (Seasonal Mean = 0.03 ± 0.005 ppm) - | | | | | | | |
| Sudbury | (U) | 6 | 0.085 | 0.026 | 1 | 1 | 0 |
| Ottawa | (U) | 7 | 0.092 | 0.033 | 8 | 1 | 1 |
| Cornwall | (U) | 7 | 0.089 | 0.034 | 15 | 2 | 0 |
| - Region 2 (Seasonal Mean = 0.02 ± 0.005 ppm) - | | | | | | | |
| Sault Ste. Marie | (U) | 2 | 0.074 | 0.023 | 1 | 0 | 0 |
| Thunder Bay | (U) | 1 | 0.060 | 0.023 | 0 | 0 | 0 |

* Ave. of all years monitored

**Ave. results for monitoring at 6 Metropolitan Toronto locations

*Table 2. Summary of Growing Season (June, July, August) $O_2$ Data for Eastern Canada: 1976-1980.*

| Location | Years | Max. 1 hr $O_3$ | Seasonal 7 hr Mean $O_3$ | No. Hrs $O_3$ > 0.08 | 0.10 | 0.12 |
|---|---|---|---|---|---|---|
| | | All values Based on Hourly $O_3$ Data from 0900 1600 E.S.T. (7 hr/day) during June, July, August (parts per million) | | | | |
| Halifax Nova Scotia | 1976 | - | - | - | - | - |
| | 1977 | 0.12 | 0.025 | 5 | 4 | 2 |
| | 1978 | 0.09 | 0.034 | 6 | 0 | 0 |
| | 1979 | 0.09 | 0.032 | 8 | 0 | 0 |
| | 1980 | 0.09 | 0.033 | 12 | 0 | 0 |
| St. John New Brunswick | 1976 | - | - | - | - | - |
| | 1977 | - | - | - | - | - |
| | 1978 | - | - | - | - | - |
| | 1979 | - | - | - | - | - |
| | 1980 | 0.07 | 0.028 | 0 | 0 | 0 |
| Quebec City Quebec | 1976 | 0.07 | 0.020 | 0 | 0 | 0 |
| | 1977 | 0.09 | 0.028 | 9 | 0 | 0 |
| | 1978 | 0.09 | 0.020 | 3 | 0 | 0 |
| | 1979 | 0.07 | 0.016 | 0 | 0 | 0 |
| | 1980 | 0.07 | 0.012 | 0 | 0 | 0 |

***Table 3. Relationship Between Annual 1 Hour $O_3$ Maximum and Seasonal $O_3$ Mean in Ontario: 1974-1981.***

| *Annual 1 hr. Max.* $O_3$ (ppm)* | *Predicted** Seasonal*** 7 hr. Mean $O_3$ (ppm)* | *Regional Ozone Category* |
|---|---|---|
| 0.05 | 0.026 | |
| 0.06 | 0.028 | Region 3 (0.03±0.005 ppm) |
| 0.07 | 0.030 | |
| 0.08 | 0.032 | (Little or No Crop Loss) |
| 0.09 | 0.033 | |
| 0.10 | 0.035 | |
| 0.11 | 0.037 | |
| 0.12 | 0.039 | Region 4 (0.04±0.005 ppm) |
| 0.13 | 0.041 | |
| 0.14 | 0.042 | (Slight to Moderate Crop Loss) |
| 0.15 | 0.044 | |
| 0.16 | 0.046 | |
| 0.17 | 0.048 | |
| 0.18 | 0.050 | Region 5 (0.05±0.005 ppm) |
| 0.19 | 0.051 | |
| 0.20 | 0.053 | (Moderate to Severe Crop Loss) |

*Maximum hourly value on an annual basis (24 hr./day)
**Statistical correlation between Annual Max. and Seasonal Mean

Seasonal Mean = (0.18 X Annual Max.) + 0.017

Standard Error of Estimate = 0.007
n = 173 (Years X Monitoring Sites)

***Mean value for June, July and August from 0900 - 1600 E.S.T. (7 hr/day)

**Table 4. Estimated Yield Losses for Selected Ontario Crops Due to Ozone Damages**

| Crop | Ozone Region 5 Average | Ozone Region 5 Range | Ozone Region 4 Average | Ozone Region 4 Range |
|---|---|---|---|---|
| | (% Loss) | | (% Loss) | |
| White beans | 12 | (6 - 18) | 7 | (4 - 11) |
| Potato | 8 | (4 - 12) | 5 | (3 - 8 ) |
| Onion | 8 | (4 - 12) | 5 | (3 - 8 ) |
| Sweet Corn | 8 | (4 - 12) | 5 | (3 - 8 ) |
| Lettuce | 8 | (4 - 12) | 5 | (3 - 8 ) |
| Radish | 8 | (4 - 12) | 5 | (3 - 8 ) |
| Spinach | 8 | (4 - 12) | 5 | (3 - 8 ) |
| Rutabagas | 8 | (4 - 12) | 5 | (3 - 8 ) |
| Tomato | 5 | (3 - 8 ) | 2 | (1 - 3 ) |
| Cucumber | 5 | (3 - 8 ) | 2 | (1 - 3 ) |
| Green bean | 5 | (3 - 8 ) | 2 | (1 - 3 ) |
| Soybean | 3 | (2 - 4 ) | * | * |
| Grape | 3 | (2 - 4 ) | * | * |
| Wheat | 3 | (2 - 4 ) | * | * |
| Tobacco ** | 1 | (0.5 - 1.5) | 0.6 | (0.3 - 0.9) |

* No expected damages or losses.

** Loss estimate based on decrease in weight and quality of injured leaves plus loss in quality due to harvest of immature leaves to avoid injured leaves.

**Table 5. Calculated Production Increases Due to Ozone Reduction**



| Crop (1978-80 average price) | $O_3$ Region 5: 1978-1980 average crop production $P_c$ (tonnes) | $O_3$ Region 5: Calculated production increase factor $\frac{\%L}{100\%-\%L}$ | | $O_3$ Region 5: Potential production increase $\Delta P$ (tonnes) | $O_3$ Region 5: Calculated $ value of production increase | $O_3$ Region 4: 1978-1980 average crop production $P_c$ (tonnes) | $O_3$ Region 4: Calculated production increase factor $\frac{\%L}{100\%-\%L}$ | | $O_3$ Region 4: Potential production increase $\Delta P$ (tonnes) | $O_3$ Region 4: Calculated $ value of production increase |
|---|---|---|---|---|---|---|---|---|---|---|
| WHITE BEAN | | Average | 0.1364 | 1,957 | 736,654 | 51,892 | Average | 0.0753 | 3,907 | 1,470,673 |
| ($376.42/tonne) | 14,346 | Low | 0.0638 | 915 | 344,424 | | Low | 0.0417 | 2,164 | 814,573 |
| | | High | 0.2195 | 3,149 | 1,185,347 | | High | 0.1236 | 6,414 | 2,414,358 |
| POTATO | | Average | 0.0870 | 6,354 | 699,766 | | Average | 0.0526 | 15,663 | 1,724,966 |
| ($110.13/tonne) | 73,036 | Low | 0.0417 | 3,045 | 335,346 | 297,775 | Low | 0.0309 | 9,201 | 1,013,306 |
| | | High | 0.1364 | 9,962 | 1,097,115 | | High | 0.0870 | 25,906 | 2,853,028 |
| ONION | | Average | 0.0870 | 2,352 | 352,283 | | Average | 0.0526 | 2,594 | 388,529 |
| ($149.78/tonne) | 27,038 | Low | 0.0417 | 1,127 | 168,802 | 49,316 | Low | 0.0309 | 1,524 | 228,265 |
| | | High | 0.1364 | 3,688 | 552,389 | | High | 0.0870 | 4,290 | 642,556 |
| SWEET CORN | | Average | 0.0870 | 487 | 141,361 | | Average | 0.0526 | 313 | 90,854 |
| ($290.27/tonne) | 5,596 | Low | 0.0417 | 233 | 67,633 | 5,944 | Low | 0.0309 | 184 | 53,410 |
| | | High | 0.1364 | 763 | 221,476 | | High | 0.0870 | 517 | 150,070 |
| LETTUCE | | Average | 0.0870 | 125 | 39,683 | | Average | 0.0526 | 584 | 185,397 |
| ($317.46/tonne) | 1,436 | Low | 0.0417 | 60 | 19,048 | 11,097 | Low | 0.0309 | 343 | 108,889 |
| | | High | 0.1364 | 196 | 62,222 | | High | 0.0870 | 965 | 346,349 |

Table 5 (Cont'd)

| Crop | $O_3$ Region 5 | | | | | $O_3$ Region 4 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| (1978-80 average price) | 1978-1980 average crop production $P_c$ (tonnes) | Calculated production increase factor $\frac{\%L}{100\%-\%L}$ | | Potential production increase P (tonnes) | Calculated $ value of production increase | 1978-1980 average crop production $P_c$ (tonnes) | Calculated production increase factor $\frac{\%L}{100\%-\%L}$ | | Potential production increase P (tonnes) | Calculated $ value of production increase |
| RADISH ($460.35/tonne) | 4,484 | Average | 0.0870 | 390 | 179,537 | 718 | Average | 0.0526 | 38 | 17,493 |
| | | Low | 0.0417 | 187 | 86,085 | | Low | 0.0309 | 22 | 10,128 |
| | | High | 0.1364 | 612 | 281,734 | | High | 0.0870 | 63 | 29,002 |
| SPINACH ($436.21/tonne) | 590 | Average | 0.0870 | 51 | 22,373 | 1,890 | Average | 0.0526 | 99 | 43,185 |
| | | Low | 0.0417 | 25 | 10,905 | | Low | 0.0309 | 58 | 25,300 |
| | | High | 0.1364 | 81 | 35,333 | | High | 0.0870 | 164 | 71,538 |
| RUTABAGAS ($101.32/tonne) | 6,680 | Average | 0.0870 | 581 | 58,867 | 50,703 | Average | 0.0526 | 2,667 | 270,220 |
| | | Low | 0.0417 | 206 | 20,872 | | Low | 0.0309 | 1,567 | 158,768 |
| | | High | 0.1364 | 911 | 92,303 | | High | 0.0870 | 4,411 | 446,923 |
| TOMATO ($359.03/tonne) | 10,104 | Average | 0.0526 | 531 | 190,645 | 10,668 | Average | 0.0204 | 218 | 78,269 |
| | | Low | 0.0309 | 312 | 112,017 | | Low | 0.0101 | 108 | 38,775 |
| | | High | 0.0870 | 879 | 315,587 | | High | 0.0309 | 330 | 118,480 |
| CUCUMBER ($235.68/tonne) | 2,347 | Average | 0.0526 | 123 | 28,989 | 1,940 | Average | 0.0204 | 40 | 9,427 |
| | | Low | 0.0309 | 73 | 17,205 | | Low | 0.0101 | 20 | 4,714 |
| | | High | 0.0870 | 204 | 48,073 | | High | 0.0309 | 60 | 14,141 |
| GREEN BEAN ($522.03/tonne) | 577 | Average | 0.0526 | 30 | 15,661 | 3,531 | Average | 0.0204 | 72 | 37,586 |
| | | Low | 0.0309 | 18 | 9,397 | | Low | 0.0101 | 36 | 18,793 |
| | | High | 0.0870 | 50 | 26,102 | | High | 0.0309 | 109 | 56,901 |

**Table 5 (Cont'd)**

| Crop (1978-80 average price) | $O_3$ Region 5: 1978-1980 average crop production $P_c$ (tonnes) | $O_3$ Region 5: Calculated production increase factor $\frac{\%L}{100\%-\%L}$ | | $O_3$ Region 5: Potential production increase P (tonnes) | $O_3$ Region 5: Calculated \$ value of production increase | $O_3$ Region 4: 1978-1980 average crop production $P_c$ (tonnes) | $O_3$ Region 4: Calculated production increase factor $\frac{\%L}{100\%-\%L}$ | | $O_3$ Region 4: Potential production increase P (tonnes) | $O_3$ Region 4: Calculated \$ value of production increase |
|---|---|---|---|---|---|---|---|---|---|---|
| SOYBEAN ($210.65/tonne) | 737,073 | Average | 0.0309 | 22,776 | 4,797,764 | 84,877 | Average | | No expected production increases | |
| | | Low | 0.0204 | 15,036 | 3,167,333 | | Low | | | |
| | | High | 0.0417 | 30,736 | 6,474,538 | | High | | | |
| GRAPE ($292.95/tonne) | 997 | Average | 0.0309 | 31 | 9,081 | 63,060 | Average | | No expected production increases | |
| | | Low | 0.0204 | 20 | 5,859 | | Low | | | |
| | | High | 0.0417 | 42 | 12,304 | | High | | | |
| WHEAT ($98.52/tonne) | 461,497 | Average | 0.0309 | 14,260 | 1,404,895 | 331,462 | Average | | No expected production increases | |
| | | Low | 0.0204 | 9,415 | 927,566 | | Low | | | |
| | | High | 0.0417 | 19,244 | 1,895,919 | | High | | | |
| TOBACCO ($2,825.99/ tonne) | 68,722 | Average | 0.0101 | 694 | 1,961,237 | 20,466 | Average | 0.0060 | 123 | 347,597 |
| | | Low | 0.0503 | 346 | 1,012,393 | | Low | 0.0030 | 61 | 172,385 |
| | | High | 0.0152 | 1,045 | 2,953,160 | | High | 0.0091 | 186 | 525,634 |

Table 6. Summary of Monetary Value of Production Increases Due to Ozone Reduction

| Crop | $/tonne (1978-80 average) | Calculated $ Value of Production Increases ($ 000) $O_3$ Region 5 | | | $O_3$ Region 4 | | | $O_3$ Regions 5 & 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Low* | Average* | High* | Low | Average | High | Low | Average | High |
| SOYBEAN | 210.65 | 3,167 | 4,798 | 6,475 | - | - | - | 3,167 | 4,798 | 6,475 |
| POTATO | 110.13 | 335 | 700 | 1,097 | 1,013 | 1,725 | 2,853 | 1,348 | 2,425 | 3,950 |
| TOBACCO | 2,825.99 | 1,012 | 1,961 | 2,953 | 172 | 348 | 526 | 1,184 | 2,300 | 3,479 |
| WHITE BEAN | 376.42 | 344 | 737 | 1,185 | 815 | 1,471 | 2,414 | 1,159 | 2,208 | 3,599 |
| WHEAT | 98.52 | 928 | 1,405 | 1,896 | - | - | - | 928 | 1,405 | 1,896 |
| ONION | 149.78 | 169 | 352 | 552 | 228 | 389 | 643 | 397 | 741 | 1,195 |
| RUTABAGAS | 101.32 | 21 | 59 | 92 | 159 | 270 | 447 | 180 | 329 | 539 |
| TOMATO | 359.03 | 112 | 191 | 316 | 39 | 78 | 118 | 151 | 269 | 434 |
| SWEET CORN | 290.27 | 68 | 141 | 221 | 53 | 91 | 150 | 121 | 232 | 371 |
| LETTUCE | 317.46 | 19 | 40 | 62 | 109 | 185 | 346 | 128 | 225 | 408 |
| RADISH | 460.35 | 86 | 180 | 282 | 10 | 17 | 29 | 96 | 197 | 311 |
| SPINACH | 436.12 | 11 | 22 | 35 | 25 | 43 | 72 | 36 | 65 | 107 |
| GREEN BEAN | 522.03 | 9 | 16 | 26 | 19 | 37 | 57 | 28 | 53 | 83 |
| CUCUMBER | 235.68 | 17 | 29 | 48 | 5 | 9 | 14 | 22 | 38 | 62 |
| GRAPE | 292.95 | 6 | 9 | 12 | - | - | - | 6 | 9 | 12 |
| TOTAL | | 6,304 | 10,640 | 15,252 | 2,647 | 4,663 | 7,669 | 8,951 | 15,303 | 22,921 |